Nano-Multiplication-Region Avalanche Photodiodes and Arrays

Oxide embedding structures and nanoscale multiplication regions would afford improvements in performance.

NASA's Jet Propulsion Laboratory, Pasadena, California

Nano-multiplication-region avalanche photodiodes (NAPDs), and imaging arrays of NAPDs integrated with complementary metal oxide/semiconductor (CMOS) active-pixel-sensor integrated circuitry, are being developed for applications in which there are requirements for high-sensitivity (including photon-counting) detection and imaging at wavelengths from about 250 to 950 nm. With respect to sensitivity and to such other characteristics as speed, geometric array format, radiation hardness, power demand of associated circuitry, size, weight, and robustness, NAPDs and arrays thereof are expected to be superior to prior photodetectors and arrays including CMOS active-pixel sensors (APSs), charge-coupled devices (CCDs), traditional APDs, and microchannel-plate/CCD combinations.

Figure 1 depicts a conceptual NAPD array, integrated with APS circuitry, fabricated on a thick silicon-on-insulator wafer (SOI). Figure 2 presents selected aspects of the structure of a typical single pixel, which would include a metal oxide/semiconductor field-effect transistor (MOSFET) integrated with the NAPD. The NAPDs would reside in silicon islands formed on the buried oxide (BOX) layer of the SOI wafer. The silicon islands would be surrounded by oxide-filled insulation trenches, which, together with the BOX layer, would constitute an oxide embedding structure. There would be two kinds of silicon islands: NAPD islands for the NAPDs and MOSFET islands for in-pixel and global CMOS circuits. Typically, the silicon islands would be made between 5 and 10 μm thick, but, if necessary, the thickness could be chosen outside this range. The side walls of the silicon islands would be heavily doped with electron-acceptor impurities (p^+-doped) to form anodes for the photodiodes and guard layers for the MOSFETs.

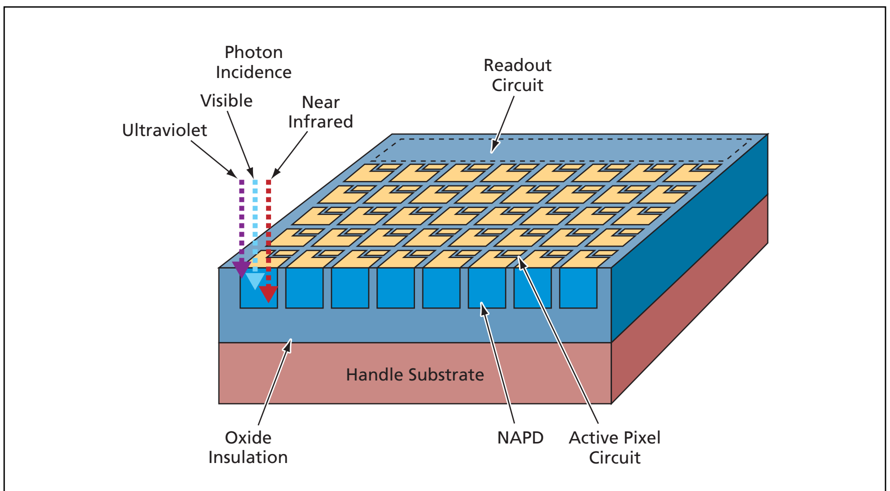

Figure 1. A **Typical NAPD Array**, characterized by a high fill factor, would be integrated with active pixel circuits and an on-chip readout circuit.

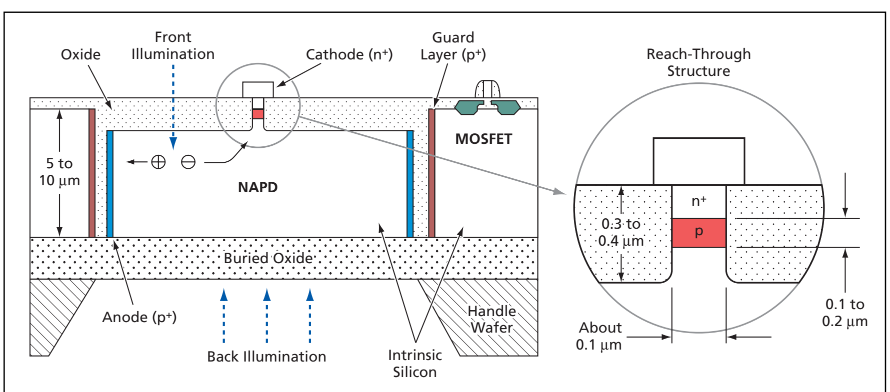

Figure 2. **Each Pixel** of an array like that of Figure 1 would contain an NAPD structure integrated with an active pixel circuit structure that, in this example, would be a MOSFET structure.

A nanoscale reach-through structure at the front (top in the figures) central position of each NAPD island would contain the APD multiplication region. Typically, the reach-through structure would be about 0.1 μm in diameter and between 0.3 and 0.4 nm high. The top layer in the reach-through structure would be heavily doped with electron-donor impurities (n^+-doped) to make it act as a cathode. A layer beneath the cathode, between 0.1 and 0.2 nm thick, would be p-doped to a concentration $\approx 10^{17}$ cm^{-3}. A thin n^+-doped polysilicon pad would be formed on the top of the cathode to protect the cathode against erosion during a metal-silicon alloying step that would be part of the process of fabricating the array. This NAPD structure would be amenable to either front or back illumination. To enable back illumination, it would be necessary to etch away, from underneath the NAPD silicon islands, the corresponding portions of a handle wafer supporting the SOI substrate.

The advantages of the NAPD concept over prior photodetector and array concepts are attributable to the oxide embedding SOI structure and the nanoscale multiplication region. The electrically insulating property of the oxide embedding structure would prevent cross-talk among pixels. The

nanoscale design of the multiplication region could be tailored to obtain unique avalanche properties. In contrast, (1) the pixels of a traditional APD array are all built on one common substrate, leading to severe cross-talk and (2) a traditional APD contains a relatively large multiplication region, within which electron avalanches are localized to a few small volumes. Efforts have been made to obtain uniformity in the multiplication regions of traditional APDs, but inasmuch as electron avalanches are very sensitive to the local electric-field fluctuations, it is difficult to obtain uniformity in large arrays of conventional APDs.

This work was done by Xinyu Zheng, Bedabrata Pain, and Thomas Cunningham of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).

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Tailored Asymmetry for Enhanced Coupling to WGM Resonators

Surfaces are made to have optimum combinations of curvatures in orthogonal planes.

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Coupling of light into and out of whispering-gallery-mode (WGM) optical resonators can be enhanced by designing and fabricating the resonators to have certain non-axisymmetric shapes (see figure). Such WGM resonators also exhibit the same ultrahigh values of the resonance quality factor (Q) as do prior WGM resonators. These WGM resonators are potentially useful as tunable narrow-band optical filters having throughput levels near unity, high-speed optical switches, and low-threshold laser resonators. These WGM resonators could also be used in experiments to investigate coupling between high-Q and chaotic modes within the resonators.

For a WGM resonator made of an optically nonlinear material (e.g., lithium niobate) or another material having a high index of refraction, a prism made of a material having a higher index of refraction (e.g., diamond) must be used as part of the coupling optics. For coupling of a beam of light into (or out of) the high-Q resonator modes, the beam must be made to approach (or recede from) the resonator at a critical angle determined by the indices of refraction of the resonator and prism materials. In the case of a lithium niobate/diamond interface, this angle is approximately 22°.

For a beam of laser light traveling through the prism and having a typical axisymmetric cross-sectional power density that varies as a Gaussian function of radius from its cylindrical axis, the cross section of the phase front changes from circular to elliptical at the interface. In the case of the lithium niobate/diamond interface, the ratio between the lengths of the semimajor and semiminor axes of the ellipse is about 2.7. In order to optimize the coupling of the beam into the high-Q modes of the resonator, the ratio between the horizontal and vertical curvatures of the resonator must be made to equal the aforesaid material-dependent ratio between the lengths of the axes of the ellipse. (Here, "vertical" and "horizontal" refer to planes onto which are projected the narrowest and widest views, respectively, of the resonator, as in the figure.) It is difficult to fabricate a WGM resonator surface to such an exacting specification at a specific point on its surface, but the task can be simplified as described next if one does not insist on a specific location.

If the WGM resonator is shaped to have a constant radius of curvature at its periphery as seen in a vertical plane but is asymmetrical (or at least non-axisymmetric) in a horizontal plane (for example, if its shape in a horizontal plane is elliptical), then its horizontal radius of curvature and the ratio between the two curvatures varies continuously with position along the periphery. Consequently, by suitable choice of the shape, it is possible to make the ratio between these curvatures equal the desired material-dependent ratio at some location along the periphery.

Several working prototype WGM resonators have been designed and fabricated according to this concept. In tests, these resonators exhibited Q values of about 10^8 and coupling efficiencies >0.7.

This work was done by Makan Mohageg and Lute Maleki of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).

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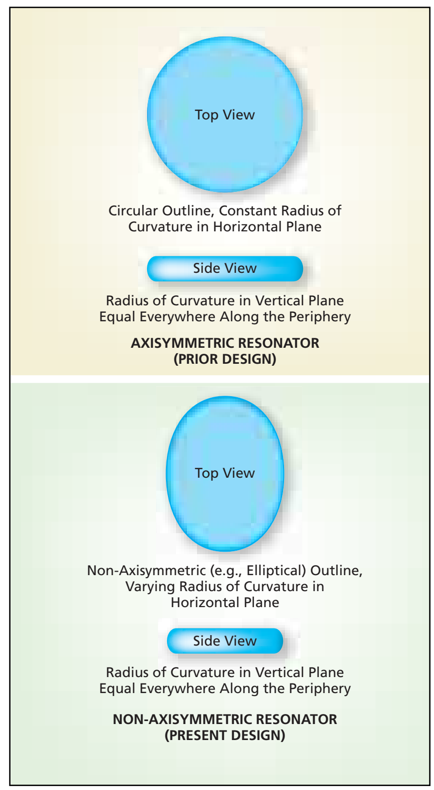

In the **Non-Axisymmetric Resonator**, the variation of curvature along the periphery in the horizontal plane is chosen such that the ratio between the horizontal and vertical curvatures has the optimum value at some location.

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